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Groundwater level changes with a focus on agricultural areas in the Mid-Atlantic region of the United States, 2002–2016

Yan Dong[a], Chengsheng Jiang[b], Mayhah R. Suri[c], Daphne Pee[d], Lingkui Meng[a], Rachel E. Rosenberg Goldstein[b,c,*]

[a] School of Remote Sensing and Information Engineering, Wuhan University, Wuhan, Hubei 430079, China
[b] Maryland Institute for Applied Environmental Health, University of Maryland School of Public Health, College Park, MD 20742, USA
[c] Department of Agricultural & Resource Economics, College of Agriculture & Natural Resources, University of Maryland, College Park, MD 20742, USA
[d] University of Maryland Extension, College of Agriculture & Natural Resources, University of Maryland, College Park, MD 20742, USA

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ABSTRACT

Climate change impacts all water sources, including high quality groundwater that supplies agricultural irrigation in many regions of the United States. This study assessed groundwater level changes in the U.S. Mid-Atlantic region with a focus on cultivated areas. Trends of groundwater level were estimated using linear regression, and examined for shallow, medium, and deep depths across physiographic regions of Mid-Atlantic. A hotspot analysis was conducted to identify spatial clusters of wells with rising or declining groundwater levels. In addition, differences in the percentage of cultivated area with declining groundwater between cultivated land categories was examined at the county level. From 2002–2016, the Mid-Atlantic region had an overall decline in groundwater level (0.06 m/yr, 95% CI: 0.03, 0.09) although groundwater changes varied by physiographic regions. The Coastal Plain physiographic region was dominated by declining groundwater wells (48%) and had the most significant groundwater level declines (0.23 m/yr, 95% CI: 0.19, 0.26). Significant groundwater level rises were detected in Southern Virginia adjacent to the Chesapeake Bay (0.92 m/yr on average), which could be due to the cessation of groundwater withdrawal from one of the region's largest groundwater users. In the Mid-Atlantic region, shallow groundwater was found to have slight rising trends (0.08 m, $p < 0.05$) while deeper groundwater showed distinctive declining trends (1.36 m, $p < 0.05$) between 2002 and 2016. There were significantly more cultivated areas with declining groundwater levels (88% vs. 35%, $p < 0.05$) in counties with high percentages of cropland (> 50%) compared to areas covered by less cropland. As climate and human pressures increase, it will be critical to identify and evaluate alternative water sources, such as reclaimed water, to sustain agricultural production and protect groundwater resources.

1. Introduction

Groundwater is a key resource in the United States (U.S.), used for critical human needs such as drinking water, household and hygiene needs, and agricultural production. The leading use of groundwater in the U.S. is agricultural irrigation, which accounts for 65% of groundwater withdrawals (Maupin et al., 2010). The U.S. Mid-Atlantic region is water-rich, so only four percent of cropland in this region is irrigated (Abler and Shortle, 2000; Boryan et al., 2012). However, within irrigated farm systems in the Mid-Atlantic, groundwater was the largest source of agricultural irrigation water (53%) (Maupin et al., 2010). The exact percentage of irrigated cropland varies within the Mid-Atlantic, with some areas relying more heavily on irrigation, including the upper Eastern Shore of Maryland and Delaware ("Acres of Irrigated Land as Percent of Land in Farms Acreage: 2012," 2012).

Groundwater refers to unconfined surficial (shallow) and deep confined aquifers. The U.S. Northeast and eastern seaboard, including the Mid-Atlantic region, primarily contains shallow groundwater (Fan et al., 2013). Shallow groundwater is often used in agriculture as it supplies soil water and can serve as a reserve especially in times of drought (Fan et al., 2013; Pulido-Bosch et al., 2018). Shallow groundwater is also more readily impacted by precipitation and climate change than confined aquifers (Russo and Lall, 2017). Confined aquifers are usually located deeper under the land surface in the Mid-Atlantic

* Correspondence to: Department of Agricultural & Resource Economics, College of Agriculture & Natural Resources, 2200 Symons Hall, College Park, MD 20742, USA.
E-mail address: rerosenb@umd.edu (R.E. Rosenberg Goldstein).

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region and can be recharged by rainfall that infiltrates through the water table. Shallow groundwater also recharges the groundwater found in deeper confined aquifers (Denver et al., 2014). In effect, withdrawals of deep groundwater are nonrenewable because of slow recharge rates (Gorelick and Zheng, 2015). Excessive groundwater withdrawals have the potential to cause groundwater depletion or groundwater quality deterioration (Pulido-Bosch et al., 2018). In irrigated agricultural areas, groundwater supply is an essential factor for crop growth, and groundwater quality may also impact food safety.

Parts of the Mid-Atlantic region have experienced serious groundwater depletion during the last century caused by both natural and anthropogenic factors (Konikow, 2013). Since 1900, groundwater levels have declined by an estimated 6.4 km^3 by 2008 in the Coastal Plain physiographic region found in Maryland, Delaware and Virginia (Konikow, 2013). In the last 40 years, groundwater withdrawal for irrigation has increased steadily in the eastern U.S. due to drought pressures on agricultural production, partially resulting from warmer temperatures and increased evaporation (Reilly et al., 2008). Withdrawals from the Maryland area of the Coastal Plain aquifer have caused groundwater levels to decline by tens of meters (Shedlock et al., 2006). In some areas of the southern Virginia Coastal Plain, groundwater levels declined more than 30 m, dropping levels below mean sea-level elevation (Masterson et al., 2011). In addition, the amount of precipitation falling in very heavy events increased by over 70% between 1958 and 2012 (Easterling et al., 2017; Walsh et al., 2014). Heavy rain events can also induce changes in groundwater levels, with some water infiltrating to the water table, but much running off and not reaching groundwater (van Gaalen et al., 2013).

Climate change can directly influence groundwater trends, and indirectly affect irrigation-water demand related to agriculture production (Taylor et al., 2013). Understanding the effects of climate change, such as intense precipitation and sea-level rise, on groundwater can inform policies, plans, and best management practices for water resources management and sustain groundwater availability for both human health and economic growth. Climate change impacts on groundwater might extend to multiple sectors of the economy, causing changes in agricultural product prices or employment opportunities available to farmers (Abler and Shortle, 2000). As groundwater resources are diminished, there is an increasing need to identify and evaluate alternative water sources, such as reclaimed water, for use in agriculture.

To our knowledge this is the first comprehensive study to determine groundwater level changes across all physiographic regions in the Mid-Atlantic region with a focus on agricultural areas. In this study we 1) describe characteristics of groundwater levels in the Mid-Atlantic region; 2) illustrate trends of groundwater level from 2002 to 2016; 3) assess spatial correlation of groundwater level changes; and 4) examine groundwater level declines in cultivated areas in the Mid-Atlantic region. By evaluating groundwater levels within multiple states using a large number of measurements over multiple years, we have targeted an appropriate scale to advance groundwater governance issues.

2. Methods

2.1. Study Area

Our study area consisted of six states from the U.S. Mid-Atlantic region: Delaware, Maryland, Pennsylvania, the District of Columbia, Virginia, and West Virginia as defined by the U.S. Environmental Protection Agency (EPA) Region 3 (2018). The average annual temperature is approximately 11 °C in this region (Res et al., 2000). Historical records (1890–2002) show that average annual precipitation in the Mid-Atlantic ranges from 76 to 178 cm (Reilly et al., 2008). Over the Mid-Atlantic region, the average annual runoff is between 30 and 127 cm, and the spatial distribution of runoff is similar to the precipitation distribution (Trapp Jr and Horn, 1997). This area has four principal physiographic regions: the Coastal Plain, the Piedmont, the Valley and Ridge, and the Appalachian Plateau. The Coastal Plain region, which borders the Atlantic Ocean, has aquifers consisting mainly of semi-consolidated to unconsolidated rocks. The Piedmont region is located in the lower eastern portion of the Appalachian Mountains, and has aquifers of mainly consolidated rocks, locally overlain by unconsolidated deposits. Further east, the Valley and Ridge region is underlain by layered and folded sedimentary rocks; its principal aquifers consist of carbonate rocks and sandstones and large alluvial fans along the Blue Ridge margin (Nelms et al., 2016). The Appalachian Plateaus region is contiguous with the Valley and Ridge, but characterized by relatively flat rocks. Consolidated sedimentary rocks make up the Appalachian Plateau aquifers (Res et al., 2000; Trapp Jr and Horn, 1997).

2.2. Groundwater data collection

Groundwater level measurements were obtained from the National Water Information System (NWIS, https://waterdata.usgs.gov/nwis), a resource managed by the US Geological Survey (USGS). Water depth records—water level below land surface—were downloaded for the period of 2002–2016. Water year, defined by USGS as the year from Oct. 1 to Sep. 30, was applied to calculate annual average groundwater depth for all wells. Across the Mid-Atlantic region, 10,808 total measurements of annual average groundwater depth, ranging from 0 to 145.93 m, were collected from 575 wells during the 2002–2016 period. These measurements of wells were classified as shallow ($< = 6.7$ m), medium (6.7–30 m) and deep (> 30 m). The 100-m threshold was used to categorize deep groundwater (Russo and Lall, 2017). The 6.7 m threshold was the median calculated from 8110 non-deep measurements of groundwater wells.

2.3. Calculating Groundwater depth

Depth measurements of wells were used to estimate groundwater levels in the Mid-Atlantic region during the period of 2002–2016. Because groundwater cannot be observed visually under the land surface, groundwater assessments are dependent entirely upon information measured from wells, such as water level or flow data (Reilly et al., 2008). First, the proportions of groundwater depth in shallow, medium, and deep were calculated within each physiographic region (Coastal Plain, Piedmont, Ridge and Valley and Plateau). A chi-square test was used to determine any significant differences in water depth between the four physiographic regions. Next, average depth to groundwater was calculated at the county level. Within each county, water depth data between 2002 and 2016 were averaged to represent the county's groundwater level. Subsequently, average depth to groundwater by county was mapped.

2.4. Groundwater change analysis

To analyze groundwater level changes, only groundwater wells which had at least 12 measurements of annual average groundwater depth from 2002 to 2016 were included. Least-squares linear regression was used to fit time-series water depth data of each well. The coefficient derived from the fitting model suggested the average water-level change rate (m/yr) and indicated the directional trend (“positive” for rising and “negative” for declining) during the study period. Wells were then categorized as shallow, medium, and deep according to their multi-year averaged depth-to-water values during the study period. Model coefficients were used to identify rising trend wells and declining trend wells in each depth category. Average groundwater depth was also calculated over the following five year intervals in order to compare groundwater level changes among shorter periods: 2002–2006, 2007–2011 and 2012–2016. T-tests were conducted to assess differences in mean groundwater depths between the five year intervals.

The regional groundwater level trend was estimated from point-

based measurements (rising/declining trend) through spatial interpolation. Moran's I calculation in ArcGIS 10.3 was used to evaluate the degree of spatial autocorrelation of groundwater change over the Mid-Atlantic region. Moran's I is a commonly used statistic to evaluate the degree of spatial autocorrelation between adjacent locations (Li et al., 2007; Moran, 1950).

Point estimates of groundwater changes were interpolated to the whole study area through "Topo to Raster" tool in ArcGIS 10.3 following the method used by McGuire (McGuire, 2014). The regional groundwater level trend was categorized as rising, declining, and no substantial change. Areas divided into categories of rising or declining experienced groundwater level changes greater than 0.015 m/year. The "no substantial change" classification was applied to areas whose absolute change was less than 0.015 m/year.

2.5. Groundwater hotspot analysis

A hotspot analysis was conducted to identify spatial clusters of wells with rising or declining groundwater levels from 2002 to 2016. The "Hot Spot Analysis" tool in ArcGIS 10.3 was used to determine groundwater change hotspots (Getis and Ord, 1992; Ord and Getis, 1995). After detecting hotspots, time-series depth data was mapped for hotpots whose average water-level change rates were greater than 0.6 m/yr between 2002 and 2016.

2.6. Groundwater and cultivated area associations

Associations between groundwater level changes and cultivated land cover were calculated at the county level. The 2016 Cultivated Layer, a data set released by the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS), was used to identify areas with cultivated land cover (Boryan et al., 2012). The percentage of cultivated coverage of each county was calculated and then grouped into categories of ≤ 5%, 6–15%, 16–50%, or > 50%. Critical values of 5% and 15% were the median and the third quartile of counties' cultivated coverage percentages, respectively. In this study, counties with greater than 50% cultivated land were defined as high-density cropland region. Percentages of cultivated land with declining groundwater were calculated for counties categorized by their cultivated coverage, not including counties with ≤ 5% cultivated coverage. T-tests were used to examine differences in percentage of cultivated area with declining groundwater between cultivated land categories.

2.7. Statistical analysis

All statistical analyses were performed using R version 3.4.2 (R Core Team, 2017). All geographic analyses were done with ArcGIS 10.3 (Redlands, CA, USA).

3. Results

3.1. Regional pattern of groundwater level

Groundwater depths—categorized as shallow, medium, and deep—have a noticeable variation across the four physiographic regions within the Mid-Atlantic region (Table 1). Among the 10,808 groundwater measurements included in the study, there were 2698 measurements in deep wells (> 30 m), 3997 measurements in medium wells, and 4113 measurements in shallow wells. The observed water depths of the Coastal Plain region were 33% shallow, 33% medium, and 34% deep. The Coastal Plain region had the highest percentage of deep groundwater measurements (34%) among the physiographic regions in the Mid-Atlantic. The other three regions were overwhelmingly underlain with shallow or medium groundwater (Table 1). The Ridge and Valley and Plateau regions had approximately twice as many medium depth measurements (62% for both) as shallow measurements (35% and 30%). The reverse is true of the Piedmont region, which had twice as many shallow well measurements (64%) compared to medium well measurements (32%), implying a higher water table than other regions.

Fig. 1 shows groundwater levels by county and physiographic region in the Mid-Atlantic region between 2002 and 2016. Eighty-seven percent of measured counties had groundwater levels less than 30 m to land surface. Specifically, 56 counties (33% out of counties included) were categorized as shallow and 90 counties (54%) were categorized as medium groundwater depth. In the three regions of Piedmont, Ridge and Valley, and Plateau, there were only six counties with deep groundwater, with the majority of counties containing medium or shallow groundwater. Deep groundwater levels were typically concentrated in the counties of the Coastal Plain region. Focusing on the Coastal Plain region, there were 16 counties (29%) with deep groundwater levels between 31 and 62 m distributed along the eastern edge, running from north to south. Meanwhile, counties on the Delmarva peninsula were dominated by shallow and medium depth water levels. In addition, counties lacking in groundwater observations were mostly located in the southwestern Mid-Atlantic, including large portions of West Virginia (73%) and Virginia (55%).

3.2. Changes in groundwater levels

3.2.1. Overall groundwater level changes

Among the 575 wells that met the groundwater level trend analysis inclusion criteria, 56% had declining groundwater levels, while 44% experienced rises in groundwater levels (Fig. 2). The average water-level change rate was −0.06 m/yr (95% CI: −0.09, −0.03; declining trend) from 2002 to 2016. There were 268 groundwater wells with significant water-level changes, 69% declining and 31% rising. The average rate of increase for these wells was 0.28 m/yr (95% CI:0.2, 0.37), and the average rate of decline was −0.31 m/yr (95% CI: −0.36, −0.27). Of all the wells included in the study, 307 did not experience significant groundwater level changes during the study period.

3.2.2. Comparative groundwater changes in physiographical regions

The results of the Moran's I analysis (Moran's Index = 0.18, z-score = 9.19 and $p < 0.001$) indicated well-measured water level changes have features of spatial autocorrelation in the study area. This suggests that groundwater level changes around nearby locations are probably dependent, and support the regional spatial interpolation as well.

At the regional scale, areas categorized as rising or declining trends had water-level changes greater than 0.015 m/year between 2002 and 2016. Among the four physiographic regions, the Piedmont was the only region with large-scale patterns of rising groundwater (71%) (Fig. 2), and groundwater levels in this region increased 0.07 m per year on average. Forty-eight percent of the Coastal Plain region had declining groundwater level trends, including six counties on the Maryland Eastern Shore (Cecil, Kent, Queen Anne's, Caroline, Talbot and Dorchester), southern Maryland, and northeastern Virginia adjacent to Chesapeake Bay (Fig. 2). In the Coastal Plain, the declining rate of groundwater level was 0.23 m/yr (95% CI: 0.19, 0.26) on average. Areas at the southern edge of Virginia and the southern Delmarva Peninsula had rising groundwater level trends, accounting for 35% of the Coastal Plain region. The lack of observed data in the south of Ridge and Valley and Plateau regions increased uncertainties when estimating groundwater change, so these segments of the physiographic regions were excluded from additional analyses. Groundwater in western Pennsylvania showed a rising trend, whereas 23% of central and northeast Pennsylvania had declining groundwater level trends.

3.2.3. Groundwater level changes and water depth

Fig. 3 displays average rates of groundwater level change with respect to water depths for all 575 wells included in the study, both those with significant changes (n = 268) and those that did not change

Table 1
Number of groundwater measurements by physiographic region and groundwater depth, U.S. Mid-Atlantic region, 2002–2016.

Water Depth	Physiographic Region n (%)					*p*-value
	Coastal Plain	Piedmont	Ridge and Valley	Plateau	Total	
Shallow[a]	2385 (33)	1207 (64)	235 (35)	286 (30)	4113 (38)	< 0.05
Medium[b]	2380 (33)	596 (32)	417 (62)	604 (62)	3997 (37)	< 0.05
Deep[c]	2526 (34)	71 (4)	21 (3)	80 (8)	2698 (25)	< 0.05
Total	7291 (100)	1874 (100)	673 (100)	970 (100)	10,808 (100)	

[a] < =6.7 m.
[b] 6.7–30 m.
[c] > 30 m.

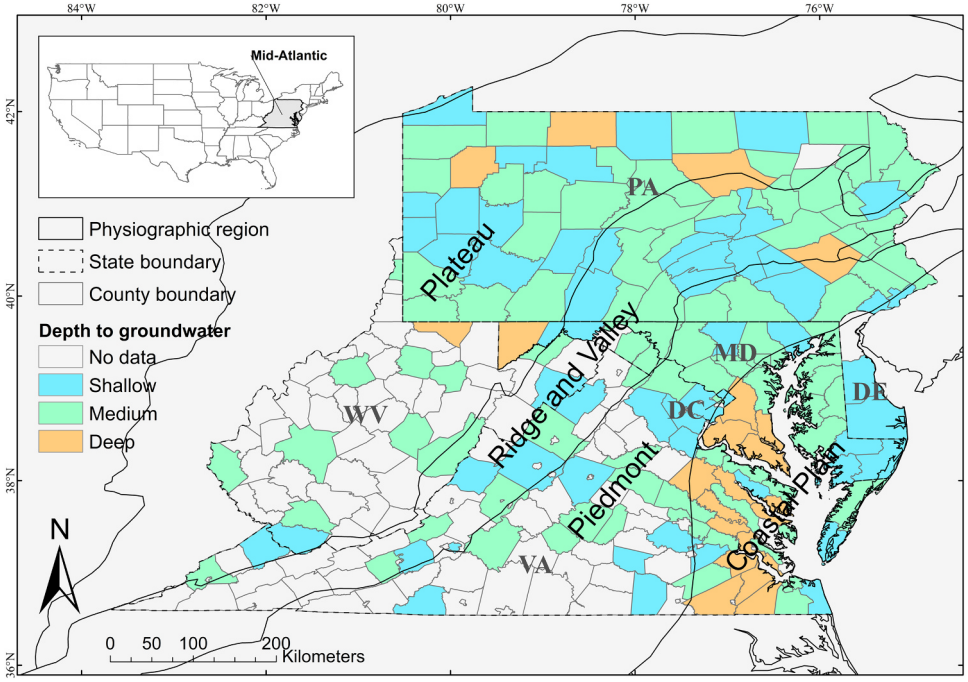

Fig. 1. Average depth to groundwater in the U.S. Mid-Atlantic region by county, 2002–2016. Categorized as shallow (< = 6.7 m), medium (6.7–30 m) and deep (> 30 m). Grey color means no groundwater level measurements during 2002–2016.

significantly during the study period (n = 307). Generally, different depth categories had various patterns of groundwater level change. In the shallow category, the number of rising groundwater wells (n = 125) was nearly double the number of declining wells (n = 67). In contrast, medium and deep wells were more likely to show declining trends. This was particularly true for the deep category, which had 110 declining wells (73%) and only 41 rising wells (27%). These trends indicate that shallow groundwater presented an overall rising trend while deeper groundwater showed a declining trend in the Mid-Atlantic Region from 2002 to 2016. We also found that the magnitude of the groundwater-level changes became more distinctive with increasing depth. In the deep category, rising wells had mean groundwater level changes of 0.35 m/yr and in declining wells it was 0.31 m/yr (Fig. 3). In comparison, mean groundwater level values were only 0.03 and 0.03 m/yr for rising and declining shallow groundwater wells, respectively (Fig. 3). Another finding was that deep groundwater had greater variation in rates of change, as compared to shallow and medium groundwater.

3.2.4. Groundwater level changes in interval periods

Fig. 4 shows average depth to groundwater taken over the study's entire 15-year period (2002–2016), as well as at 5-year intervals. The average depth to groundwater was 3.2 m, 15.9 m, and 57 m for shallow, medium, and deep wells, respectively. Wells in both medium and deep categories showed significant groundwater-level declines (corresponding to a numeric increase in depth) from the first measurement period of 2002–2006 to the second period of 2007–2011. Deep wells had the most significant groundwater level declines between the two periods with their average depth increasing by 1.36 m ($p < 0.05$). Medium and deep groundwater levels showed a consistent declining trend from the first 5-year period to the last 5-year period (2012–2016), with changes being smaller in the latter 10 years (Figs. 4b and 4c). For shallow wells, groundwater levels declined between the first and second 5-year study periods ($p < 0.05$), but there was a groundwater level increase (0.13 m on average) from 2012 to 2016 compared to 2007–2011 (Fig. 4a) ($p < 0.05$). The overall change was a slight rise of 0.08 m for shallow groundwater level between 2002 and 2006 and 2012–2016 ($p < 0.05$).

3.3. Temporal-spatial characteristics of groundwater changes

Two hotspot clusters were detected among all of the wells included in this study: 1) on the southern border of Virginia that showed significant rising groundwater level trends (Fig. 5b); and 2) in southern Maryland showing significant groundwater level declines (Fig. 5c). In Southern Virginia, eight wells with significant increases over 2002–2016 were distributed in the Isle of Wight, Southampton, and Suffolk counties (Fig. 5b), and experienced groundwater level rises in

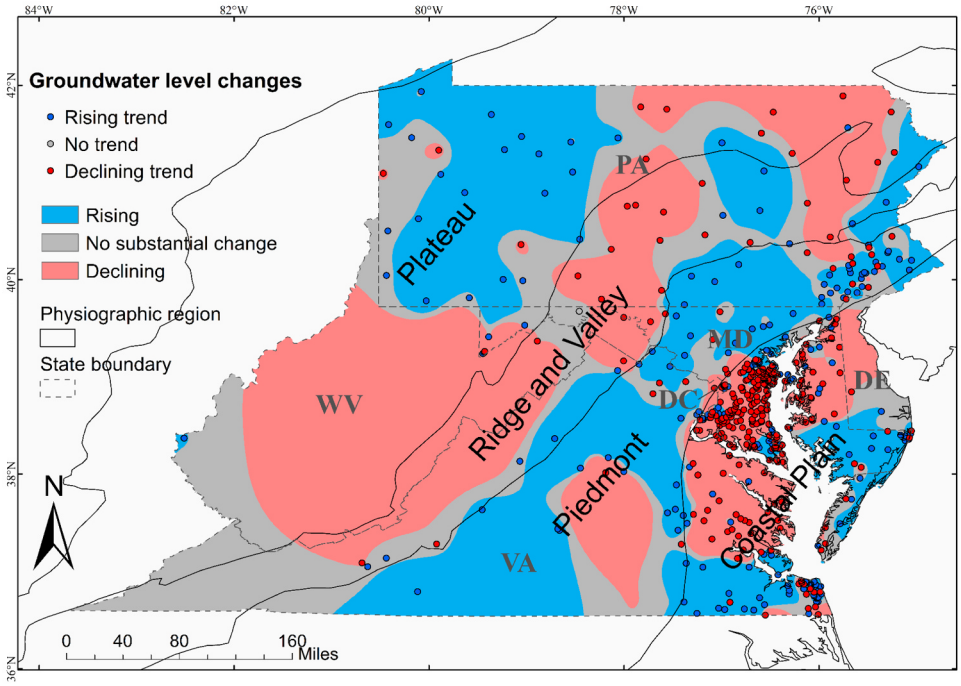

Fig. 2. Groundwater level changes in the U.S. Mid-Atlantic region, 2002–2016. Points are observed groundwater wells. Point-based groundwater level rises/declines are derived from linear regression of water depth data and significant with p-values < 0.05. Regional groundwater level changes are obtained from interpolating point-based changes and are categorized into rising, declining and no substantial change.

the range of 0.26–2 m/yr (mean = 0.92 m/yr). The hotspot cluster in southern Maryland is composed of 46 groundwater wells with declining groundwater level trends located in Anne Arundel, Prince George's, Charles, Calvert, and St. Mary's counties (Fig. 5c). In the southern Maryland cluster, we omitted three wells (shown as plain red dots in Fig. 5c) because they were physically isolated from the other wells and therefore had less geographical connection. These hotspots experienced groundwater level declines ranging from 0.03 to 1.58 m/yr (mean = 0.45 m/yr). Notably, both hotspot clusters sit in areas with deep groundwater (Figs. 1 and 5).

A subset of 13 wells with groundwater level change greater than 0.6 m/yr was selected to more closely examine water-level changes over time. Fig. 6a displays rises in groundwater levels in southern Virginia. Although rates of change varied, the trends are almost identical between the Virginia wells: the water level trended slightly downwards around 2008, then sharply increased in the next three to four years, and finally kept relatively stable in the following years, which fits better to a third-order polynomial rather than the linear trend line. The similarity of the overall patterns of these wells demonstrates that rising groundwater trends are spatially correlated. Fig. 6b describes declining groundwater trends in southern Maryland. Among the Maryland wells, five were located in northwest Charles County and exhibited similar patterns of change and had highly similar rates of change (~1.5 m/yr) (Fig. 6b). Three wells, located in central Charles County, also have similar rates of change (~0.6 m/yr) (Fig. 6b). These consistent patterns among neighboring wells confirm the strong spatial autocorrelation for declining groundwater trends.

3.4. Groundwater decline in agricultural areas

On average, 8.61% of land in the Mid-Atlantic region is under cultivation, though it varied from 0% to 64.29% at the county level (Fig. 7). Fifty-seven percent (n = 162) of counties had ≤ 5% cultivated land cover, 21% (n = 59) counties had 6–15% of cultivated area, 21% (n = 58) counties with had 16–50% of cultivated area, and 1% (n = 4) counties had > 50% cultivated area (Fig. 7a). These four high-density cropland counties were the adjacent Kent, Queen Anne's, Caroline and Talbot Counties on the Eastern Shore of Maryland (Fig. 7a).

There were significant differences in declining groundwater trends between high-density cropland region and areas covered by less cropland. Eighty-eight percent of areas with > 50% cultivated land experienced groundwater level declines between 2002 and 2016 compared to 37% of areas with 6–15% cultivated land and 33% of areas with 16–50% cultivated land (p < 0.05). No significant differences

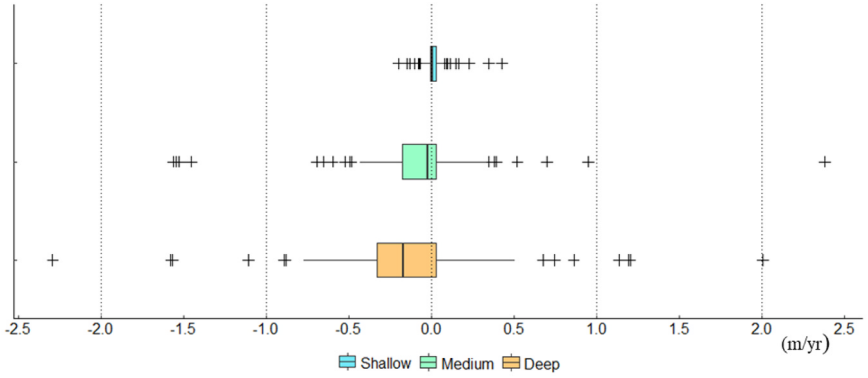

Fig. 3. Average rate of groundwater level change in shallow, medium, and deep wells, U.S. Mid-Atlantic region, 2002–2016. Wells were categorized according to their average depths from 2002 to 2016 (Shallow < =6.7 m; Medium = 6.7–30 m; Deep > 30 m).

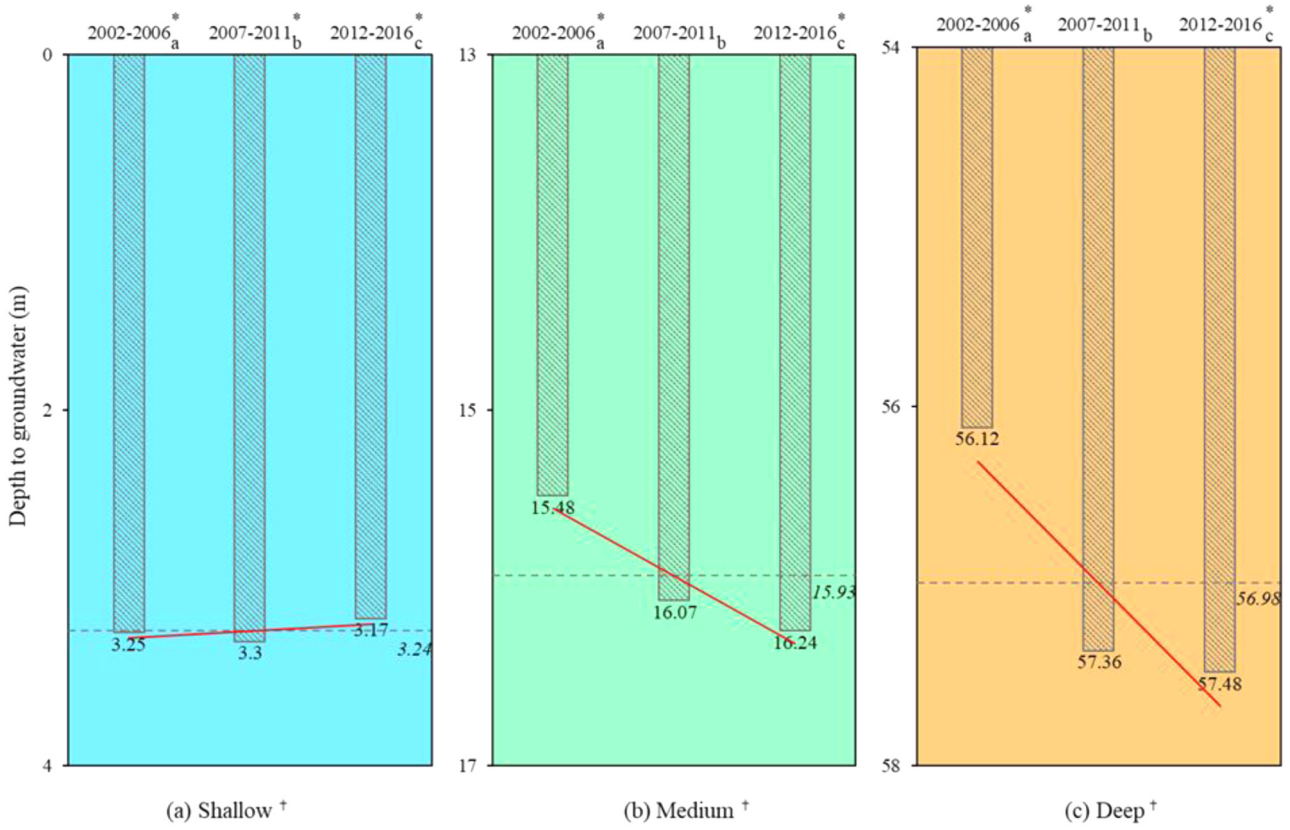

Fig. 4. Average groundwater depths over 5 year intervals in shallow, medium and deep wells, U.S. Mid-Atlantic region, 2002–2016. (a) Shallow (< =6.7 m); (b) Medium (6.7–30 m); (c) Deep (> 30 m). The dashed line shows the average groundwater depth over 2002–2006 (numeric value is under the dotted line). The red line represents the general groundwater level trend. † Wells were categorized according to their average depths during 2002–2016. [a] difference in means tested between 2002 and 2006 and 2007–2011 (* p-value < 0.05); [b] difference in means tested between 2007 and 2011 and 2012–2016 (* p-value < 0.05); [c] difference in means tested between 2002 and 2006 and 2012–2016 (* p-value < 0.05).

were observed between counties with 6–15% and 16–50% cultivated land area ($p = 0.57$). Within the highly cultivated region, the four counties had differing proportions of cultivated land experiencing groundwater decline out of total cultivated area: Kent (69%), Queen Anne's (85%), Caroline (100%) and Talbot (96%) (Fig. 7c).

4. Discussion

4.1. Groundwater level decline

Our study found that groundwater levels have generally declined in the Mid-Atlantic region between 2002 and 2016 (Fig. 2). According to wells used for groundwater change analysis, 56% of wells had declining trends compared to 44% with increasing trends. In our study, deep groundwater, which is primarily concentrated in the Coastal Plain physiographic region along the east coast from Maryland to Virginia (Fig. 1), had the highest level of groundwater decline from 2002 to 2016 (1.36 m, $p < 0.05$). Our findings are in line with previous research that found groundwater declines in the Coastal Plain and particularly within Maryland and Virginia during earlier time periods. Curtain and Dine (1995) found that groundwater levels in southern Maryland generally declined from 1946 to 1994, with levels declining steadily through the mid-1980s, and accelerating in the late 1980s. According to Soeder et al. (2007), declines in groundwater levels occurred in most aquifers of the Maryland Coastal Plain system with increasing groundwater withdrawals from 1980 to 2005. In some areas of the southern Virginia Coastal Plain, groundwater levels have declined more than 30 m putting the levels below mean sea-level elevation (Masterson et al., 2011).

We identified a hotspot cluster of groundwater level declines in Southern Maryland, including the counties of Anne Arundel, Prince George's, Charles, Calvert, and St. Mary's (Fig. 5c). The representative hotspots in Maryland show nearly linear groundwater declines during 2002–2016 (Fig. 6b). Previous studies showed that domestic water withdrawal and public water supply are the major factors causing groundwater declines in Southern Maryland (Soeder et al., 2007; Staley, 2015). In Maryland's Calvert and St. Mary's Counties, linear declining groundwater level trends were previously detected from 1980 to 2004, and were partially attributed to increasing rates of withdrawal (Soeder et al., 2007). In Charles County, Staley (2015) found that groundwater level declines were between 1 and 2 m per year and were primarily caused by groundwater withdrawal for public supply. In this study, Southern Maryland had the most significant groundwater level declines throughout the Mid-Atlantic region. Declining groundwater trends were also identified in other parts of Mid-Atlantic region, such as the northern area of the Delmarva Peninsula. Additional research is needed to determine the causes of groundwater level declines in these areas.

Some studies have shown that climate change can reduce groundwater levels because of decreased groundwater recharge from reduced precipitation or extremely heavy precipitation events (Ertürk et al., 2014). As many of the aquifers on the Delmarva Peninsula and in Southern Maryland are confined aquifers, it has been hypothesized that they might be less susceptible to both contamination from the surface and short-term climate changes ("Confined Aquifer Wells", 2017). Although shallow groundwater is more readily impacted by changes in precipitation and climate, deep groundwater is often tapped during droughts which could increase as climate change impacts grow (Russo

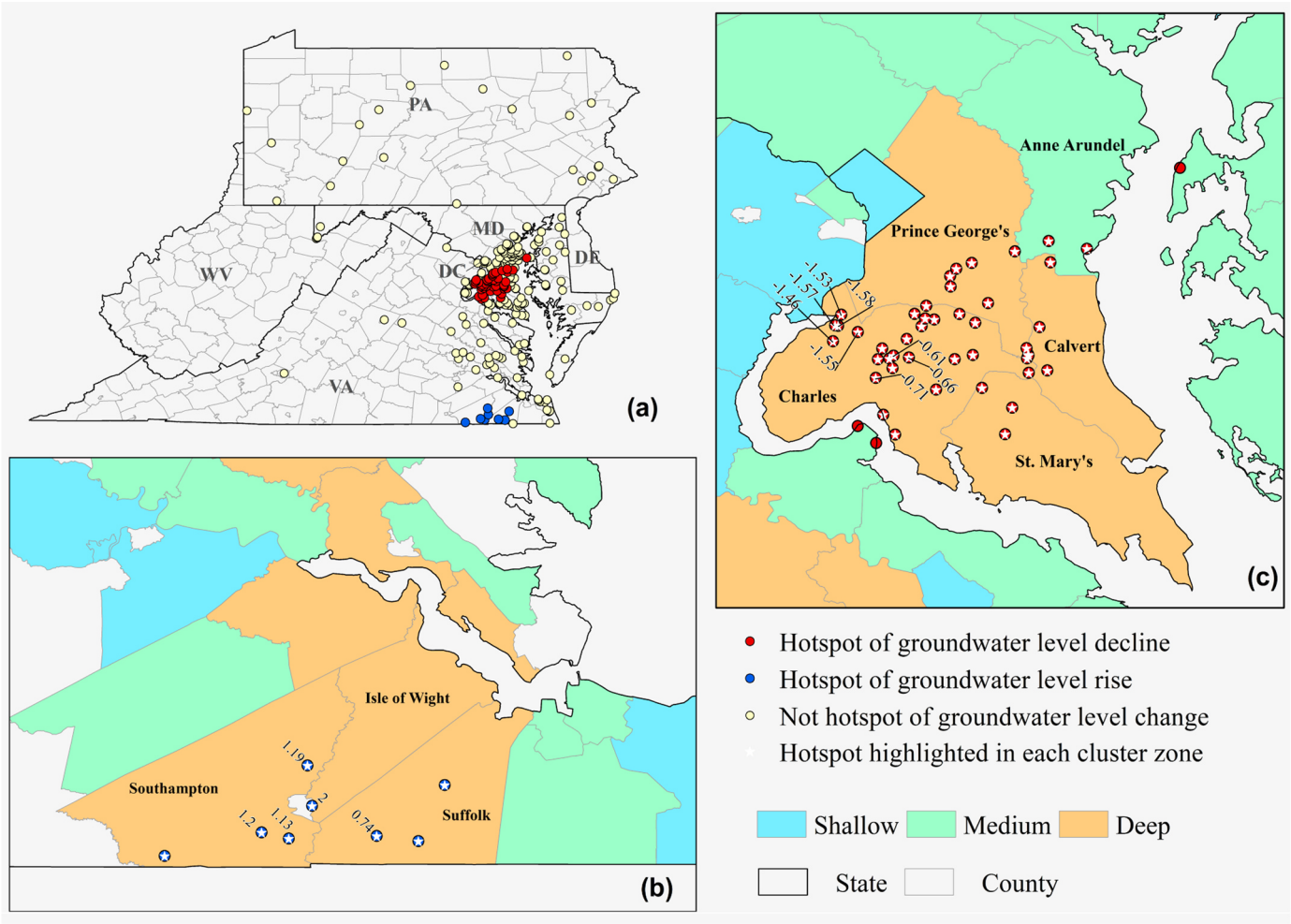

Fig. 5. Groundwater level change hotspots in the Mid-Atlantic region, 2002–2016. (a) Overall spatial distribution of groundwater level change hotspots (red or blue points represent statistically significant spatial clusters); (b) Cluster of groundwater level rise hotspots; (c) Cluster of groundwater level decline hotspots. Numbers close to wells are average rates of groundwater level change during 2002–2016.

and Lall, 2017).

It is noteworthy that the spatial autocorrelation of groundwater changes examined through Moran's I was further confirmed by similar patterns of time-series depth data in hotspot wells. Our study provides evidence to support predicting regional groundwater level change using point-measured data, because groundwater observations are mostly point-based and direct measurements over an entire region are difficult and costly as well (Najjar et al., 2010; Ning et al., 2015; Sun et al., 2009).

4.2. Groundwater level rise

Over the Mid-Atlantic region, hotspots of groundwater level rises were detected in southern Virginia, including Isle of Wight, Southampton, and Suffolk counties (Fig. 5b). This region, adjacent to the Chesapeake Bay, has seen high rates of land subsidence which could contribute to sea-level rise and increase the risk of flooding (Wade, 2016). Historical data indicate that over-pumping of groundwater was primarily responsible for land subsidence in southern Virginia (Eggleston and Pope, 2013). The local aquifer would compact as groundwater levels declined, which caused the land surface to move downward (Galloway et al., 1999). However, from 2002 to 2016, we detected significant rising groundwater level trends in southern Virginia. According to Stephenson (2014), a paper mill in Franklin, VA temporarily closed from 2009 to 2012, and reduced a large volume of groundwater withdrawal. In our study, high increases in groundwater levels, in counties adjacent to Franklin, occurred exactly during the same time period. Therefore, groundwater level rises in the hotspot area were most likely the result of ceasing pumping from wells. Groundwater injection is an approach to replenish groundwater supply, abate land subsidence, and prevent saltwater intrusion (Harner et al., 2016). The Hampton Roads Sanitation District has proposed the SWIFT (Sustainable Water Initiative for Tomorrow) project to inject more than 100 million gallons of purified wastewater per day, into the aquifer of Hampton Roads in southern Virginia to address land subsidence and saltwater intrusion (Fears, 2016).

Along the Eastern Shore of Virginia, we also found rising groundwater levels. Sallenger et al. (2012) found a high rate of sea level rise (mean = 1.97 mm/year) from Cape Hatteras to Boston through analysing tide-gauge records (1950–2009) along the North American Atlantic coast. Recent studies have shown that groundwater tables are vulnerable to sea-level rise in coastal areas, because sea-level rise could contribute to saltwater intrusion by raising the interface between intruding saltwater and overlying freshwater (Hoover et al., 2017; Nicholls and Cazenave, 2010; Rotzoll and Fletcher, 2013; Werner and Simmons, 2009). Previous observations indicate that the Virginia Eastern Shore is vulnerable to saltwater intrusion and groundwater demands in this region have not varied extensively during the past few years (Eastern Shore of Virginia Groundwater Resource Protection and Preservation Plan, 2013). The increasing groundwater level trends observed in the Eastern Shore of Virginia could be due to accelerated sea-level rise caused by climate change and extreme climate-associated

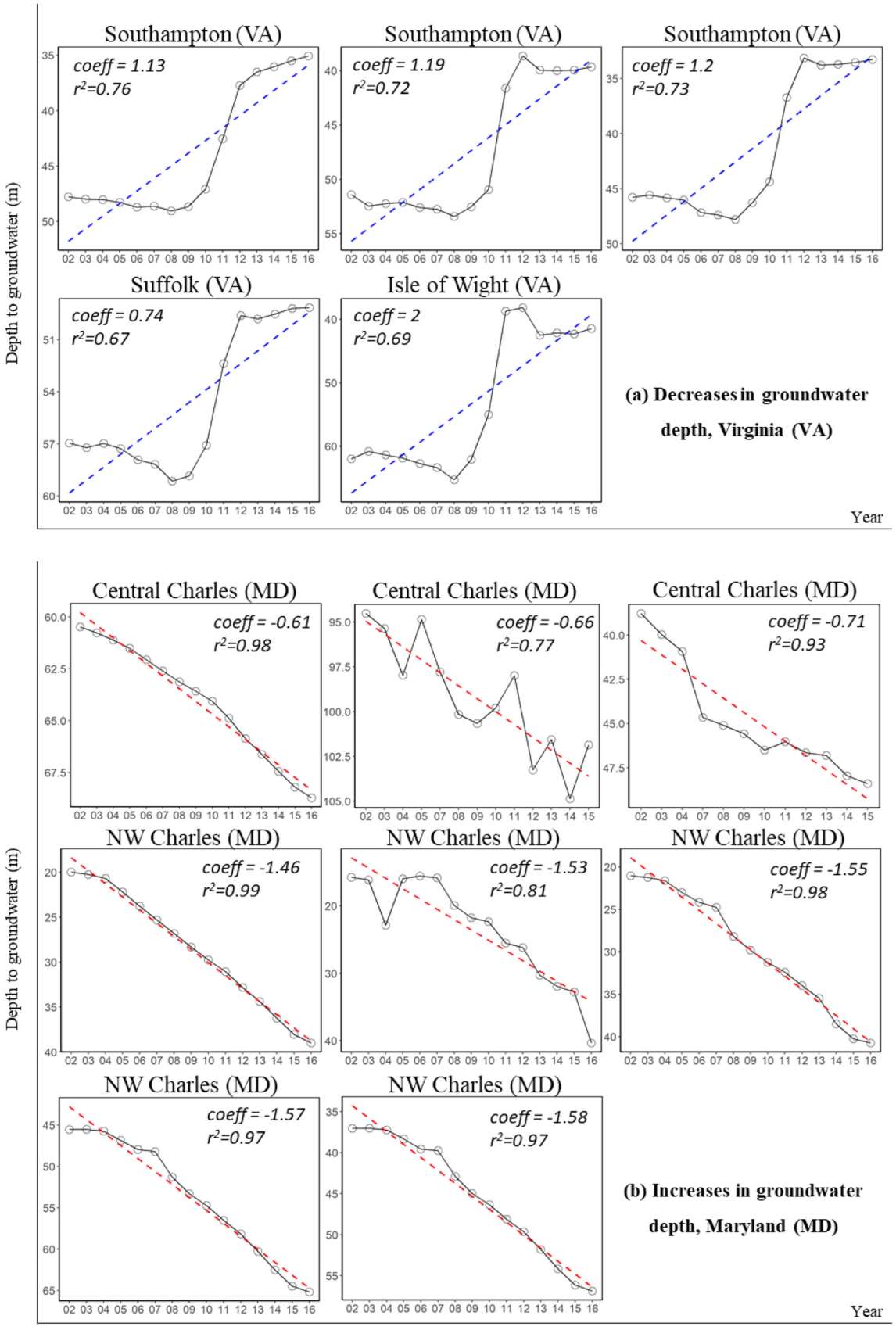

Fig. 6. Time series of groundwater depth in hotspot areas, select counties in Maryland and Virginia, 2002–2016. (a) Water depth decreased (rising groundwater level trend) in southern Virginia; (b) Water depth increased declining groundwater level trend) in southern Maryland. The title refers to the county (state) where the monitoring station is located. Blue lines correspond to rising groundwater level trends. Red lines correspond to declining groundwater level trends. Coeff is the average rate of groundwater level change (m/yr).

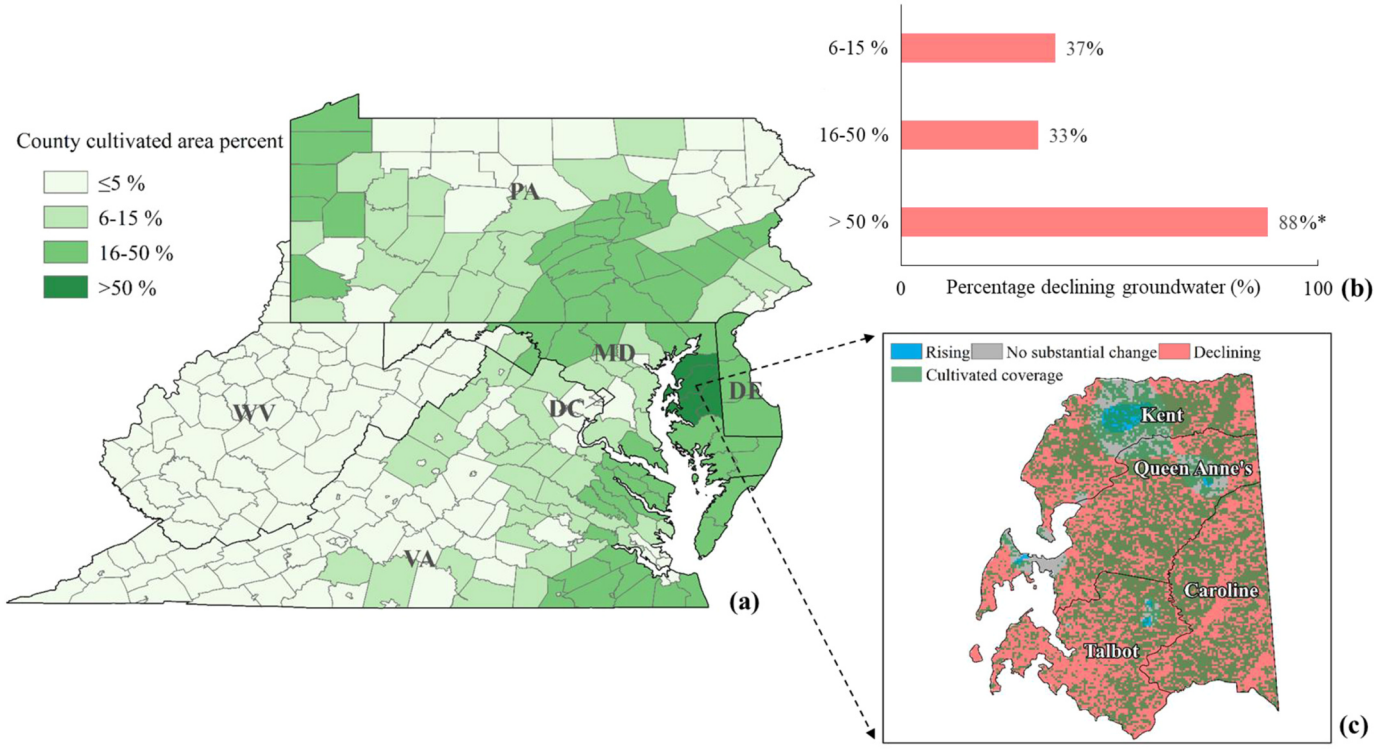

Fig. 7. Groundwater level declines in cultivated areas, Mid-Atlantic region, 2002–2016 (a) Spatial distribution of cultivated area (county level), Mid-Atlantic region; (b) Groundwater level decline by cultivated area category, 2002–2016 (*p-value < 0.05 when tested difference in percentages between category > 50% and categories of 6–15% and 16–50%); (c) Groundwater level changes overlying cultivated coverage in high-density cropland region (counties in > 50% category).

events (Barlow and Reichard, 2010).

The area of western Pennsylvania contained in the Plateau region also showed rising groundwater level trends. It has been previously documented that total groundwater withdrawals decreased within the Plateau region between 1995 and 2005 (McCoy et al., 2015), which was mainly due to a large-scale reduction in coal mining which can temporarily lower the water table (Trapp Jr and Horn, 1997). At the same time, the 15-year study period includes more wet years than dry years with respect to abundant precipitation recharge (McCoy et al., 2015). Groundwater level rise in western Pennsylvania could have resulted from both natural and human-induced mechanisms.

4.3. Differences in water-level changes by groundwater depth

Our results reveal that there are differences in water-level changes between shallow and deep groundwater wells in the Mid-Atlantic region. We detected a slight rising trend for shallow groundwater levels in the most recent 10 years (Fig. 4). Natural groundwater recharge is highly dependent on precipitation which has been influenced by climate change, especially associated extreme events, such as droughts and floods (Dams et al., 2012; Shamsudduha, 2009; Taylor et al., 2013). Shallow groundwater is vulnerable to short-term recharge fluctuations and longer-term precipitation variations, because unconfined aquifers are directly connected to earth's surface, and mainly recharged by water that filters down from the ground above. Previous studies identified significant increases in both extreme precipitation frequency and amount of precipitation over the Mid-Atlantic region for the past 50 years (Horton et al., 2014; Najjar et al., 2010). Thus, the rising trend of shallow groundwater was likely a result of the increased precipitation, acting as a major reflection of climatic variation.

In contrast to shallow wells, medium and deep wells showed declining groundwater levels throughout 2002–2016, and had higher rates of groundwater level change. Russo and Lall (2017) also found a higher percentage of deep groundwater wells experienced declining levels compared to shallows wells and concluded that deep groundwater levels were affected by both climate-associated variations and human groundwater demand. Water pumping could lead to immediate observable water-level changes, however, any changes from precipitation variability in deep aquifers would be delayed for several years because of the time needed for the recharge signal to pass through the upper aquifer (Chen et al., 2004; Gurdak et al., 2007; Hanson et al., 2006). Deep groundwater is usually less susceptible to both surface-level contamination and short-term climate change ("Confined Aquifer Wells", 2017). With precipitation increasing in the Mid-Atlantic region, the declining trends in deep groundwater were more likely due to human withdrawal of groundwater. Future studies are needed to determine if differences between shallow and deep water level changes could be a good indicator of the amount of human influence versus climatic impacts.

4.4. Associations between groundwater level decline and cultivated area

Our results showed that the most cultivated areas (> 50% cultivated land) on the Eastern Shore of Maryland had the highest percentage of groundwater declines (88%) from 2002 to 2016 (Fig. 7). Most of the groundwater level declines on the Eastern Shore were found in shallow to medium wells (Fig. 1), which are often used for agricultural irrigation ("Water Use", 2014). In areas with 6–15 and 16–50% cultivation coverage shown in Fig. 7, we did not see a significant difference in groundwater declines between categories of cultivated areas (p = 0.57).

Previous studies have shown that irrigation water demand is a leading cause of groundwater water depletion (Leng et al., 2015; Taylor et al., 2013). Agricultural irrigation accounts for approximately 20% of total groundwater withdrawal in Maryland (Schmid, 2011), however this proportion is higher on the Eastern Shore in Kent, Queen Anne's, Caroline, and Talbot counties where, on average, 49.4% of groundwater withdrawals were used for agricultural irrigation ("Water Use", 2014).

For these four counties, corn and soybeans were the top crop items by acreage, and they had the largest cultivated areas of these crops within Maryland (“ Census of Agriculture”, 2012, 2018). Agricultural irrigation can lead to groundwater level declines when the amount of water pumping exceeds natural replenishment (Bouwer, 1987; Famiglietti, 2014; Scanlon et al., 2012).

However, Ho et al. (2016) found that in Maryland, groundwater level changes were negatively correlated with agricultural water use, because non-agricultural water uses took a higher proportion of the total groundwater supply. In our study, hotspots of groundwater decline were in counties of Southern Maryland which has relatively little cultivated coverage, 9% on average (Boryan et al., 2012). In addition, the percentage of groundwater withdrawn for irrigation (6%) was much lower than of the percentage withdrawn for public and domestic supply (88%) in Southern Maryland (“Water Use”, 2014).

In this study, we did not assess groundwater changes in response to type of groundwater withdrawal (agricultural, household, industry, etc.), and cannot quantify the exact impacts of agriculture, public supply, and domestic withdrawals on groundwater in the Mid-Atlantic region. Regardless, the high percentage of groundwater declines in highly cultivated areas in our study region emphasizes the need to continue to evaluate alterative agricultural irrigation water sources, such as reclaimed water, that could provide growers with a reliable water supply, especially in times of drought.

4.5. Limitations

For the groundwater level change analyses, the tested wells were not spatially uniform, most observed wells were located in the Coastal Plain region and few wells were located in West Virginia. The uneven distribution of wells could increase uncertainty in estimating regional groundwater change. Future analyses also should investigate groundwater level changes in terms of unconfined versus confined aquifers. For the current study, we were not able to obtain information distinguishing between confined and unconfined aquifers throughout the study area. We did not limit the minimum number of observations needed to calculate annual average groundwater depth, which might affect the detection of seasonal variations in groundwater level. Moreover, errors around observations were likely to reduce the accuracy of estimating groundwater level changes, especially for areas with minor changes (less than 0.015 m/yr).

5. Conclusions

In this study, we analyzed overall groundwater level changes in the Mid-Atlantic region between 2002 and 2016. Fifty-six percent of groundwater wells in the Mid-Atlantic region have declined in the past 15 years. The Coastal Plain physiographic region had the most significant groundwater level declines. This region also contained the highest percentage of agricultural areas with large-scale groundwater level declines, but it is unknown if agricultural water demands, climactic trends like drought and heavy rain, or non-agricultural withdrawals (household) are causing changes in groundwater levels in this area. Significant groundwater level rises were detected in Southern Virginia adjacent to the Chesapeake Bay, which were the result of ceasing pumping from the wells. Shallow groundwater, often used for agriculture, had slight rising trends while deeper groundwater showed distinctive declining trends in the Mid-Atlantic region from 2002 to 2016. Deep groundwater wells were concentrated in the Coastal Plain region and had the highest observed groundwater level declines during the study period (1.36 m, $p < 0.05$). It is possible that shallow groundwater is more vulnerable to climate change impacts and deeper groundwater is influenced by a combination of human activities and climate effects. In the United States, municipal, agricultural, and industrial water use is highly dependent on groundwater withdrawals. Facing increasing groundwater resource demands deriving from human needs and climate variability, it is important to further understand the relationships between agriculture, climate change impacts, and groundwater levels, and continue to evaluate other water sources such as reclaimed water for agricultural purposes.

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